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Dark QCD Perspective Inspired by Strong-CP Problem at QCD Scale

Bin Wang[*] , Shinya Matsuzaki[†] and Hiroyuki Ishida[‡]

[*,†] *Center for Theoretical Physics and College of Physics, Jilin University, Changchun 130012, China*

[‡] *Center for Liberal Arts and Sciences, Toyama Prefectural University, Toyama 939-0398, Japan*

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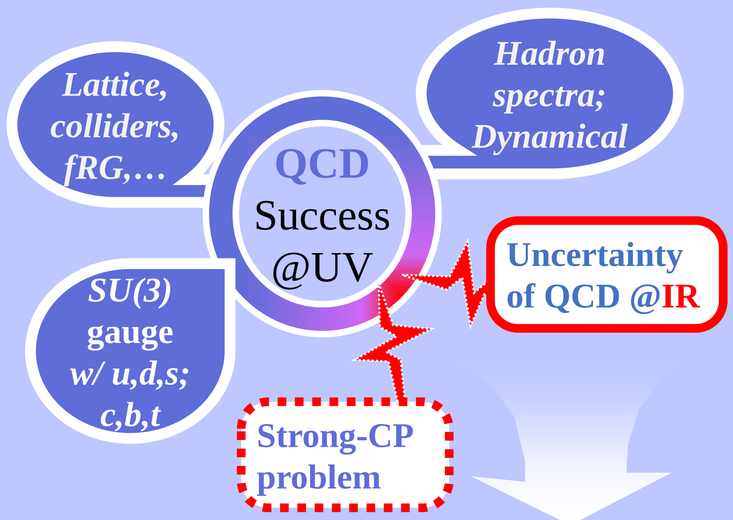


Nanohertz GWs ⇒ FOPT @ **QCD scale**

Sweet spot for DM→SM **@ 1 GeV**

BSM+QCD ⇒ **New picture of thermal history** @QCD epoch

New Physics might be @ QCD Scale

Model Setups

SM QCD — Gluon

$\phi = \frac{S}{\sqrt{2}} e^{i\frac{P}{v_S}}$, SSB $\Rightarrow \frac{v_S}{\sqrt{2}} e^{\frac{iP}{v_S}}$ ($v_s \sim 10^5$ TeV);

***P*: to be ultra-light PQ axion**

Dark QCD extension

G_d: dark gluon

Q_{aA}, Massless

χ_A: $\mathcal{L}_{g_\chi} = -g_\chi(\phi \bar{\chi}_L \chi_R + h.c.) \Rightarrow m_\chi = \frac{1}{\sqrt{2}} g_\chi v_S \sim 1$MeV

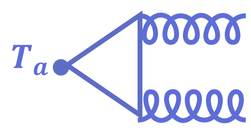
$U(4)_L \times U(4)_R (N_{fd} = 3+1) \Rightarrow U(3)_Q|_{QCD} \times U(1)_\chi$

J.E.Kim Model: Massless dark quarks only and @ $f_a \approx 10^{9-12}$ MeV

dχSB@$\Lambda_d \gtrsim \Lambda_c \sim 1$ GeV

$\bar{F}_L F_R \Rightarrow \langle \bar{F}F \rangle U_d$, $\langle \bar{F}F \rangle \sim (600MeV)^3$, $U_d = \exp\left(2i\frac{\pi_d^A}{f_{\pi d}} T_A\right)$, $U_d \to g_L^\dagger U_d g_R$,

$f_{\pi d} \sim 200$MeV



$$\partial^\mu J^0_{\mu 5} = \frac{2}{\sqrt{8}} i m_\chi \bar{\chi}\gamma_5\chi - \frac{g_c^2}{32\pi^2}\frac{3}{\sqrt{8}} G\cdot\tilde{G} - \frac{g_d^2}{32\pi^2}\frac{4}{\sqrt{8}} G_d\cdot\tilde{G}_d\,,$$

$$\partial^\mu J^{15}_{\mu 5} = \frac{3}{2\sqrt{6}} i m_\chi \bar{\chi}\gamma_5\chi + \frac{g_c^2}{32\pi^2}\frac{3}{2\sqrt{6}} G\cdot\tilde{G}\,,$$

$T_0 = \frac{1}{2\sqrt{2}} I_{4\times4}$, $T_{15} = \frac{1}{2\sqrt{6}} diag(1,1,1,-3)$; $\Rightarrow$ $\pi_d^0 \equiv \eta_d$, $\pi_d^{15} \equiv a$

Hybrid ALP's relaxation

$$V_{\eta',\eta_d,a,P}\Big|_{\text{mass}} = 2\left[\sum_{q=u,d,s} m_q\langle\bar{q}q\rangle\cos\left(\frac{2\eta'}{\sqrt{6}f_\pi}\right) + m_\chi\langle\bar{F}F\rangle\cos\left(\frac{\eta_d}{\sqrt{2}f_{\pi_d}} + \frac{3a}{\sqrt{6}f_{\pi_d}} + \frac{P}{v_S}\right)\right]$$

$$V_{\eta',\eta_d,a,P}\Big|^{\text{flavor-universal}}_{\text{anomaly}} = \chi_{\text{top}}^{\text{QCD}}\cdot\cos\left(\bar{\theta}_{\text{QCD}} + \frac{3\eta'}{\sqrt{6}f_\pi} + \frac{3\eta_d}{2\sqrt{2}f_{\pi_d}} - \frac{3a}{2\sqrt{6}f_{\pi_d}}\right) + \chi_{\text{top}}^{\text{dQCD}}\cdot\cos\left(\bar{\theta}_{\text{dQCD}} + \frac{\sqrt{2}\eta_d}{f_{\pi_d}}\right)$$

$$V_{\eta',\eta_d,}\Big|^{\text{flavor-non-universal}}_{\text{anomaly}} = \frac{1}{2}m_{\eta'}^2\eta'^2 + \frac{1}{2}m_{\eta_d}^2\eta_d^2.$$

J.E.Kim Model: **No physical $\bar{\theta}_{dQCD}$** (or to say, removed by η_d)

$\bar{\theta}_{eff} = \bar{\theta}_{QCD} - \bar{\theta}_{dQCD}$

$\bar{\theta}_{QCD}$ ⟷ $\bar{\theta}_{QCD}$ (via Q_{aA})

$P|_{PQ\ axion}$ = $\langle\eta'\rangle = \langle\eta_d\rangle = 0$, $\left\langle\frac{a}{f_a}\right\rangle = \left\langle\frac{P}{2v_S}\right\rangle = 0$

Mass structure

E.O.M for η', $\eta_d \Rightarrow \langle\eta'\rangle, \langle\eta_d\rangle = 0$, since $m_{\eta_d} \geq m_{\eta'} \sim 1$ GeV $\gg m_a \gg m_P$

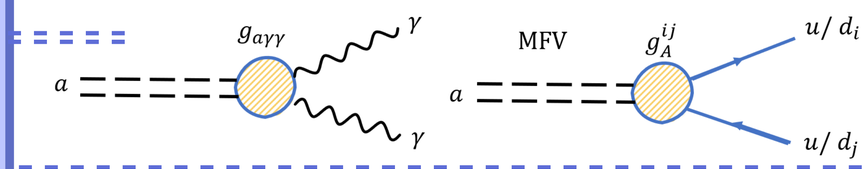
$$m_a \simeq 140\,\text{MeV} \times \left(\frac{\langle -\bar{F}F\rangle}{(600\,\text{MeV})^3}\right)^{1/2}\cdot\left(\frac{200\,\text{MeV}}{f_a}\right)\cdot\left(\frac{m_\chi}{0.45\,\text{MeV}}\right)^{1/2}.$$

Mimic π^0

$$m_P^2 \simeq \frac{1}{4v_S^2}(-\chi_{\text{top}}^{\text{QCD}}) \simeq \left(0.1\,\text{eV}\times\left(\frac{|\chi_{\text{top}}^{\text{QCD}}|}{(76\,\text{MeV})^4}\right)^{\frac{1}{2}}\cdot\left(\frac{2.8\times10^5\,\text{TeV}}{v_S}\right)\right)^2$$

m_P is determined by m_a=140 MeV

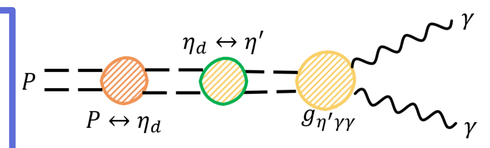
ALPs Phenom.



w/o 1^{st}-generation quark coupling to avoid the perfect mixing

$P \to \gamma\gamma$

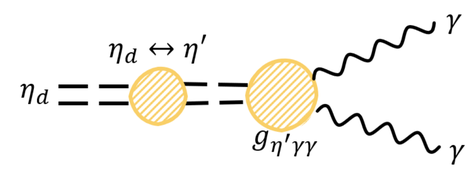
$$\Gamma_P = \Gamma_{\eta'\to\gamma\gamma}\cdot\left(m_P\cdot\frac{\sqrt{6}m_a^2\sqrt{|\chi_{\text{top}}^{\text{QCD}}|}}{2m_{\eta'}^2 f_\pi m_{\eta_d}^2}\right)^2\left(\frac{m_P}{m_{\eta'}}\right)^3 \simeq 10^{-45}\text{eV}\cdot\left(\frac{\text{m}_\text{P}}{1\text{eV}}\right)^4\cdot\left(\frac{2\text{GeV}}{\text{m}_{\eta_\text{d}}}\right)^5$$



$\tau_{P(m_P=1eV)} = 1/\Gamma_P > t_U$, ALP-DM candidate

$\eta_d \to$ dark mesons

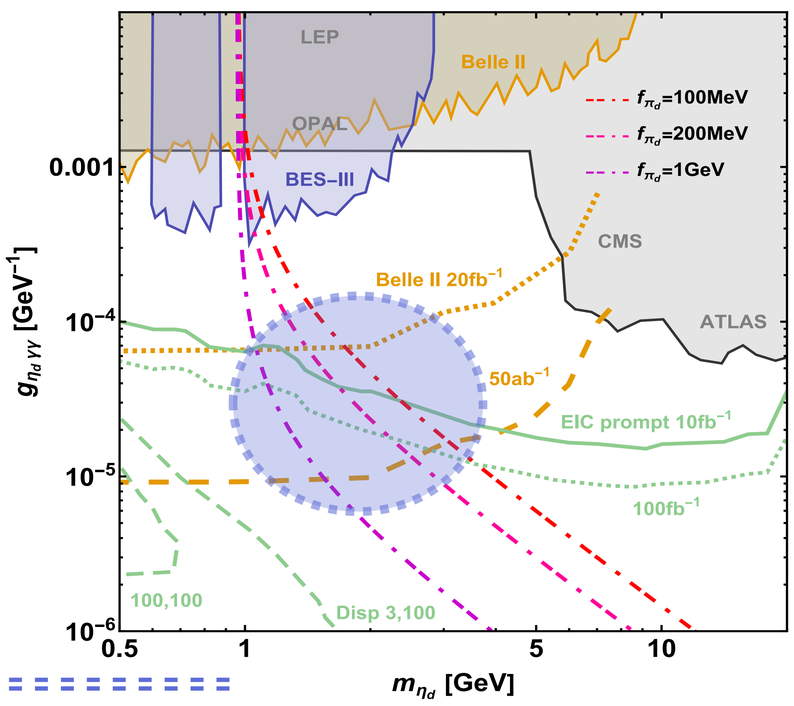
$$\Gamma[\eta_d \to S_a + a] \sim \frac{m_{\eta_d}^3}{16\pi f_{\pi_d}^2}\left(1 - \frac{m_{S_a}^2}{m_{\eta_d}^2}\right),$$



$\eta_d \to \gamma\gamma$

$$g_{\eta_d\gamma\gamma} = \frac{3\sqrt{3}|\chi_{\text{top}}^{\text{QCD}}|}{4f_\pi f_{\pi_d}}\cdot\frac{1}{m_{\eta_d}^2 - m_{\eta'}^2}\cdot g_{\eta'\gamma\gamma} \simeq 7.2\times10^{-5}\,\text{GeV}^{-1}\times\left(\frac{200\,\text{MeV}}{f_{\pi_d}}\right)\cdot\left(\frac{1\,\text{GeV}^2}{m_{\eta_d}^2 - m_{\eta'}^2}\right).$$

Smoking − Gun − ALP

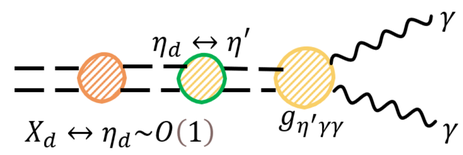


3γ events @ future **Belle-II, EIC and** BES-III(mainly around 1 GeV),

the ALP w/ the mass range : **$1 - 3.2$ GeV** have the highest possibility to be detected!

X_d: $J^{PC} = 0^{+-}$ Pseudo dark glueball, $\mathcal{O}(1)$ mixing w/ η_d

$$g_{X_d\gamma\gamma} = \theta_{\eta_d,X_d}\cdot g_{\eta_d\gamma\gamma}\Big|_{p^2=m_{X_d}^2} = \theta_{\eta_d,X_d}(m_{X_d}^2)\frac{3\sqrt{3}|\chi_{\text{top}}^{\text{QCD}}|}{4f_\pi f_{\pi_d}}\cdot\frac{1}{m_{X_d}^2 - m_{\eta'}^2}\cdot g_{\eta'\gamma\gamma}\,.$$



Summary & discussions

- Extend SM to QCD × dQCD, $\Lambda_d \gtrsim \Lambda_c \sim 4\pi f_\pi \sim 1GeV$.
- DQCD induced hybrid axion relaxation:

  Various and **correlated phenomenology**:

  1. m_a =140 MeV---*a:* **mimic π^0**, $a \to \gamma\gamma$& **flavor changing**.
  2. m_P <1 eV---*P:* invisible axion.
  3. $m_{\eta_d} \sim$ O(1) GeV---η_d: $\gamma\gamma$/dark meson decay,**@ Belle II, EIC,** BESIII .
- GWs from:
  1. The U(1) PQ complex scaler; cosmic string collisions…
  2. QCD × dQCD **supercooling FOPT**(can be referred to many-flavor QCD)
- DM: PBHs from supercooling FOPT, long-lived *P*-ALP , $n_d = \chi\chi\chi$(dark neutron),…

A rough estimation of the thermal relic abundance of n_d could be done by assuming the standard freeze-out scenario for this annihilation with the size of the classical cross section $\langle\sigma v\rangle \sim 4\pi/m_{n_d}^2$. This crude approximation could be justified in the large-N_c and -N_d limit, where the dark baryon behaves like almost static, nonrelativistic, and a classical rigid body with finite radius (i.e. impact parameter) of $\mathcal{O}(1/m_{n_d})$. The thermal relic abundance is then evaluated as $\Omega_{n_d}h^2 \sim \frac{10^9 x_{\text{FO}}}{\sqrt{g_*(T_{\text{FO}})}M_{\text{p}}\text{GeV}\langle\sigma v\rangle}$, where $x_{\text{FO}} = m_{n_d}/T_{\text{FO}}$ with T_{FO} being the freeze-out temperature; M_{pl} is the Planck scale $\sim 10^{18}$ GeV; $g_*(T_{\text{FO}})$ the effective degree of freedom of relativistic particle at $T = T_{\text{FO}}$. The standard freeze-out scenario gives $x_{\text{FO}} \sim 20$, and $g_*(T_{\text{FO}}) = \mathcal{O}(50)$ at T below 1 GeV [83]. The relic abundance of n_d is then estimated to be of $\mathcal{O}(10^{-9})$ for $m_{n_d} \sim 2$ GeV, which is compared with the observed abundance of the cold dark matter today ~ 0.1.

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P.S. The dark hadrons will form **exotic QCD hadrons,** e.g., $(\bar{Q}_{aA}\chi_B)(\bar{\chi}_B Q_{aA}) \sim 1$ GeV, which would be identified as multijets due to the QCD interaction,.